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Impact of Nutrients on Growth Performance, Yield and Quality Attributes of Capsicum (*Capsicum annuum* L.) under Protected and Open Field Environments

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ABSTRACT

Background: Capsicum cultivation differs significantly between open fields and protected environments (polyhouses/shade nets), with open-field being lower cost, shorter cycle, prone to weather/pests but yielding lower quality, while protected cultivation involves higher initial investment but offers superior, year-round production, better fruit quality (thicker walls, longer shelf life), efficient resource use and higher profits due to controlled climate, water, nutrients and pest/disease management, making it ideal for red varieties and export markets.

Methods: A total of ten nutrient treatments were applied under two different growing environments, following a two-factor completely randomized design (CRD) with three replications. Fifteen key parameters were recorded and analyzed, including days to 50% flowering, days to first fruit set, days to first and last fruit harvest, plant height, fruit length, fruit diameter, fruit weight, number of fruits per plant, dry weight of 100 seeds, yield per plant, yield per hectare (quintal) and ascorbic acid content. Data analysis was carried out using OPSTAT software and Microsoft excel.

Result: A significant increase in the number of fruits per plant was observed under polyhouse conditions, particularly in T_7 (22.00) in polyhouse and in open field, T_7 and T_5 both having (18.66) number of fruits per plant indicating that optimal nutrient application tailored to specific crop needs and growth stages. The highest yield per plant was recorded in T_7 (50% RDF + B @ 0.2%+ Ca @ 0.2%) with 3.35 kg, followed by T_5 (75% RDF + Ca @ 0.2%) at 3.05 kg, under polyhouse condition. The highest ascorbic acid content was observed in T_7 (50% RDF + B @ 0.2% + Ca) with 1.62 mg/ml, followed by T_8 (50% RDF + Ca @ 0.2%) with 1.37 mg/ml, under polyhouse conditions. The study underscores the importance of environment-specific nutrient management strategies for maximizing capsicum productivity and quality. These findings contribute valuable insights for horticultural practices and can aid in formulating nutrient schedules for sustainable high-yielding capsicum production.

Key words: Capsicum, Cebrail F1, Growth, Nutrients, Openfield, Polyhouse, Quality, Yield.

INTRODUCTION

Bell pepper (*Capsicum annuum* L.), a member of Solanaceae family, is one of the most important vegetable which is native to Mexico, has attained a status of high value crop in India. The demand for pepper fruits is increasing day by day due to their pungency, delicious flavour and medicinal value. Vitamin C and pro-vitamin A are abundant in chillies, especially red ones (Bal *et al.*, 2022).

India contributes 25 per cent of the world production as capsicum is grown in almost all parts of India. In India according to recent analysis (NHB, 2024), it is grown in an area of 40 thousand hectares with a production of 627 MT and productivity of 15.7 t/ha. Red capsicums are cultivated in several states across India, with significant production in Karnataka, Himachal Pradesh, Haryana and Maharashtra. Protected cultivation, especially in greenhouses and polyhouses, plays a major role in this production, enabling year-round harvesting and higher yields. The demand for coloured capsicums, both domestically and for export, has fuelled the adoption of protected cultivation methods. Coloured capsicums increasing demand in metropolises and high potential to export overseas, if the quality standard is maintained. Which are why, more and more farms in India now days have started to switch over to greenhouse-based cultivation? The well-protected environment of a

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green house is ideally the best method to continue growing capsicum throughout the year.

Red Capsicum farming and processing can provide significant economic opportunities for rural and urban communities. Research on red capsicum yield is necessary for improving crop yields, nutritional value, addressing market demands and enhancing economic benefits of farmers.

Micronutrient deficiencies in chilli production often limit growth, reduce yield and compromise fruit quality. (Magalhaes *et al*., 2023). Micronutrients are essential for the promotion of plant growth and the optimization of yields in vegetable crops. Boron aids in cell expansion and hormone regulation, particularly auxin metabolism, which affects fruit growth. Calcium enhances membrane stability and cell integrity, supporting uniform elongation of fruit cells. Micronutrients such as boron, zinc and iron play critical roles in plant growth and development and their availability and management significantly influence crop productivity in vegetable cropping systems (Jayara *et al*., 2021). This reflects a more efficient nutrient utilization strategy and suggests that supplementing NPK with critical micronutrients can lead to improved physical fruit traits, thus supporting nutrient optimization and cost-effectiveness in cultivation practices.

The protected environment of the polyhouse, with optimal humidity and stable temperature, can enhance calcium and boron uptake and improve nutrient use efficiency in vegetable crops (Anil *et al*., 2020).

One promising approach involves the strategic application of micronutrients, which play a crucial role in physiological and metabolic processes essential for plant growth and development (Kumar *et al*., 2022). Understanding the interaction between application strategies and environmental responses is vital for developing efficient production protocols. The micronutrient application strategy depends on the crop type, soil, requirements and the planned timing of fertilizer delivery (Ahmed *et al*., 2024). The most often utilized methods for applying micronutrients are soil application, foliar spraying, hydroponic systems and fertigation. Keeping in view these points the present investigation on has been done.

MATERIALS AND METHODS

Plant materials, experimental layout and design

The experimental site geographically situated at an altitude of 640 m above sea level with latitude of 30-34°N and longitude of 70.02°E. Package of practices for production of capsicum has been followed to maintain healthy crop stand. The experiment was conducted during the rabi (winter) season of 2024-25 at ISBT Farm, School of Agriculture, Graphic Era Hill University, Dehradun to study the effect of nutrients and different growing environments *viz*., Polyhouse and Open-field, The experiment was laid out in a complete randomized design with three replications comprising ten treatment combinations of different growing environments and different doses of Micro and Macronutrients (Calcium and Boron with Cebrail F1 (Red Capsicum). Ten micronutrient treatments in sub plots *viz*.T_1= 100% RDF+B @ 0.2%+Ca@ 0.2% ,T_2= 100% RDF+Ca @ 0.2%, T_3= 100% RDF+B, @ 0.2% T_4= 75% RDF+B @ 0.2%+Ca @ 0.2%, T_5= 75% RDF+Ca, @ 0.2%, T_6= 75%RDF+B, @ 0.2% T_7= 50% RDF+B @ 0.2%+Ca @ 0.2%, T_8= 50% RDF+Ca @ 0.2%, T_9= 50% RDF+B @ 0.2%, T_{10}= Control.

Growth parameters and yield attributes

Fifteen key parameters were recorded and analyzed, including days to 50% flowering, days to first fruit set, days to first and last fruit harvest, plant height, fruit length, fruit diameter, fruit weight, number of fruits per plant, dry weight of 100 seeds, yield per plant, yield per hectare (quintal) and biochemical quality indicators such as ascorbic acid content. For facilitation of the data collection, a random selection of 5 plants was made in each treatment across three replications. The length and diameter of five fruits from each treatment was measured using a scale and averaged. Calipers were used in the central portion of the randomly selected matured fruits for taking measurements. The dry weights of seed (g) were measured separately in each treatment using 100 g of seed weight. Fresh fruit yield per plant and fresh fruit yield (q/ha) were both measured.

Chemical analysis

Ascorbic acid content of different treatment were calculated from a 5 g (Fresh weight) sample using the formulae described by Harris and Ray (1935). Ascorbic acid is estimated by titrating sample extracts against 2,6-dichlorophenol indophenol. Using oxalic acid as an acidic medium, the vitamin reduces the dye to a colorless leuco-base. The process reaches its endpoint when a persistent pink color appears. This redox reaction enables precise quantitative calculation of Vitamin C concentration

Statistical analysis

Data analysis was carried out using OPSTST software. Duncan's multiple range test (DMRT) was performed to estimate the significance of the difference among the treatments where the level of probability was 5%. A detailed calculation was completed to determine the means for all the treatments and the F-test was used to perform analyses of variance for most of the characters. The least significant difference test (LSD) was carried out for the evaluation of the significance of the differences between pairs of means. Wherever significant differences were found, the critical differences (CD) at 5% level were calculated to compare treatment means.

RESULTS AND DISCUSSION

Studying the effect of variety, micronutrient application efficiency and their interaction on growth and yield attributes helps identify the most productive crop varieties under specific nutrient regimes. It provides deep in sights into optimal fertilization strategies to enhance plant growth and yield (Prasad *et al.*, 2024). The proper physiological process assures the maximum yield (Hossain *et al.*, 2025). Our results revealed that environment has a tremendous impact on different traits such as days to 50% flowering (Table 1), days to first fruit set, days to first and last fruit harvest, plant height, fruit length, fruit diameter, fruit weight, number of fruits per plant (Fig 1) yield per plant (Fig 2) and ascorbic acid content (Fig 3).

Different application methods with different doses influence micronutrient efficiency (de Avila *et al.*, 2024). Our findings suggested that the efficiency of the combined soil application and spraying application method of mixed (B and Zn) micronutrients enhanced vegetative growth. This is because foliar application ensures quick absorption of nutrients and soil application solves long-term nutrient deficiency (Ahmed *et al.*, 2024). Yield parameters such as fresh weight of fruit, dry weight of fruit, seed weight, fresh fruit weight are effectively influenced (Table 2) by combined soil application of Macronutrient and foliar application of micronutrients.

Significant variation was observed among different nutrient treatment combinations in both conditions. Days to 50% flowering is important as it determines the earliness of crop maturity and has a direct impact on subsequent growth, fruit development and harvest time. As a perusal of Table 1, days to 50% flowering were significantly influenced by the different treatment combinations under both polyhouse and open field conditions. The treatment T_7 showed (40.66) days to 50% flowering under polyhouse and (43.33) days under open field conditions, which is not desirable for earliness. Similarly, T_5 also recorded early flowering (41.33 days in polyhouse and 42.66 days in open field), placing these two treatments among the earliest flowering categories after the control. Results are dissimilar with previous studies done by Patel *et al.* (2012) in capsicum and other solanaceous crops.

Under polyhouse conditions, the days to first fruit set ranged from 46.00 days in treatment T_7, 52.26 days in the control treatment (T_{10}) as compared to open field conditions, the duration ranged from 48.66 days (T_7) to 56.00 days (T_{10}) (Fig 1). This demonstrates that the control treatment took the longest time to initiate fruit set, indicating delayed reproductive development under standard fertilization without micronutrient enhancement. This is particularly note worthy because it suggests that the inclusion of micronutrients not only compensates for reduced macronutrient levels but can also enhance physiological processes that lead to earlier flowering and fruit development. Treatments T_5 and T_1, also performed well with early fruit set occurring around 46.16 to 48.00 days in polyhouse and 49.33 to 52.66 days in open field conditions, respectively. In terms of interaction Table 2, polyhouse gained early fruit set in 46.00 days as compared to openfield then attain fruit set in 48.66 days. The promotive effect of boron on reproductive development can be attributed to its role in pollen tube formation, fertilization and hormonal balance, which are critical for fruit set (Chaudhary *et al.,* 2006).

Under polyhouse, the earliest fruit harvest was observed in T_7 (69.66 days) Conversely, the control (T_{10}) recorded the delayed harvest at 80.00 days, indicating a delay in maturity as compared to open field conditions,

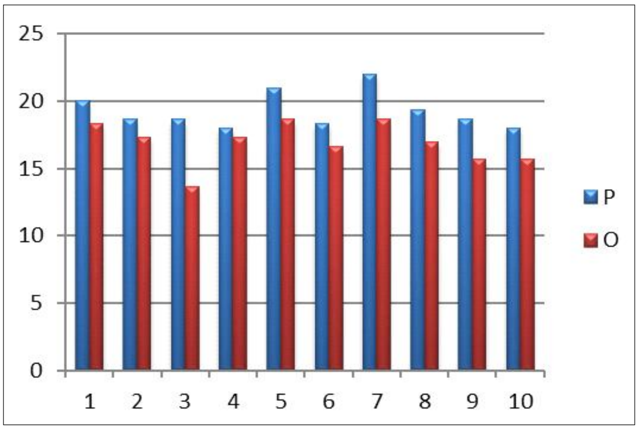

Fig 1: Number of fruit/plant.

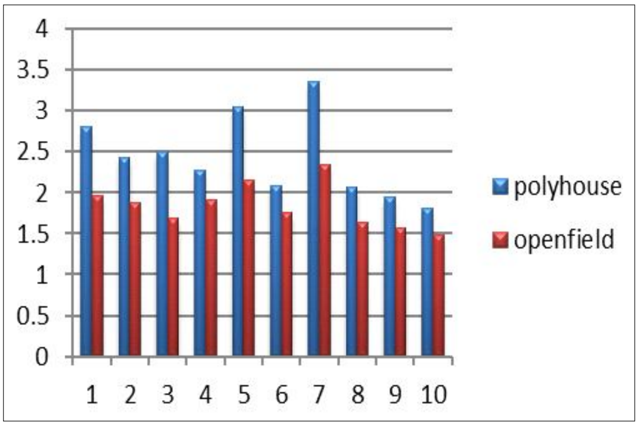

Fig 2: Yield per plant (kg).

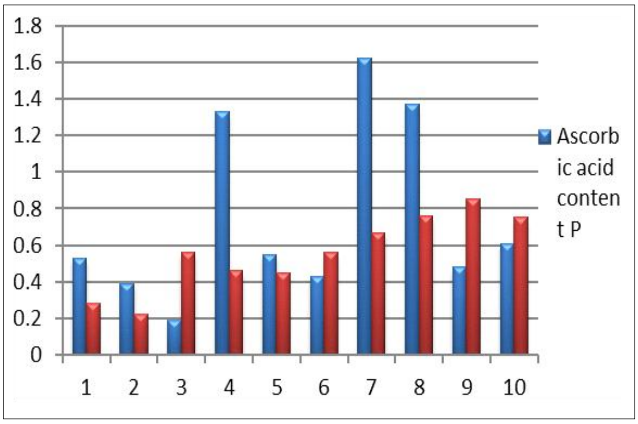

Fig 3: Ascorbic acid content in both polyhouse and openfield.

Table 1: Mean performance of capsicum under polyhouse (P) and openfield (O) condition.

Treatment	50% flowering (Days)	First fruit set (Days)	First fruit harvest (Days)	Last fruit set (Days)	No of fruit per plant	Fruit length (cm)	Av. fruit weight (gm)	Fruit diameter (cm)	Yield/ plant (kg)	Pericarp thickness (mm)	Number of seed/ fruit	Dry weight of 100 seeds (g)	Plant height (cm)	Ascorbic acid content (mg/100 g)	Number of locules/ fruit
Factor A															
Polyhouse	44.10	49.26	75.6	151.43	19.26	8.43	125.24	6.50	2.42	4.827	197.00	0.453	125.23	0.754	3.433
Openfield	45.36	52.96	81.4	149.06	16.90	7.70	86.49	5.76	1.83	4.300	204.10	0.483	106.79	0.558	3.100
GM	44.73	51.11	78.0	150.14	18.08	8.06	168.485	6.08	2.13	4.56	205.55	0.96	116.01	0.65	3.26
SE(m)	0.273	0.206	0.316	0.181	0.176	0.103	0.227	0.103	0.002	0.034	1.309	0.007	0.743	0.019	0.058
CD	0.783	0.590	0.907	0.519	0.506	0.295	0.650	0.295	0.007	0.098	3.754	0.019	2.131	0.055	0.166
Factor B															
T_1	43.83	50.33	74.66	148.50	19.16	8.00	113.27	5.16	2.38	3.50	196.66	0.443	115.83	0.408	3.16
T_2	46.00	50.33	76.00	148.83	18.00	7.50	108.91	5.16	2.15	3.81	191.83	0.423	117.41	0.308	3.16
T_3	47.33	52.00	80.33	149.33	16.16	8.00	108.84	4.66	2.08	4.01	190.00	0.450	113.31	0.377	3.00
T_4	47.00	51.75	87.50	149.16	17.66	7.83	103.71	5.33	2.09	4.31	187.83	0.442	114.16	0.897	3.16
T_5	42.00	47.75	71.83	151.00	19.88	9.66	120.33	7.66	2.60	5.00	190.16	0.438	130.13	0.505	3.50
T_6	46.33	52.16	83.16	152.16	17.50	7.83	99.16	5.50	1.91	5.26	188.66	0.502	110.45	0.498	3.16
T_7	42.00	47.33	70.50	152.83	20.33	9.66	124.33	7.83	2.85	5.30	182.00	0.512	142.90	1.147	3.50
T_8	42.50	52.50	78.00	153.16	18.16	7.66	95.65	6.33	1.85	4.61	233.33	0.477	104.50	1.070	3.00
T_9	46.66	52.83	80.50	150.00	17.16	7.33	91.77	5.50	1.75	4.45	191.00	0.473	106.81	0.670	3.16
T_{10} (Control)	40.66	54.13	82.50	147.50	16.83	7.16	92.72	8.16	1.65	5.35	254.16	0.518	104.58	0.683	3.83
GM	44.43	51.11	78.49	150.24	18.08	8.06	105.87	6.12	2.13	4.56	200.56	0.46	116.00	0.656	3.26
SE(m)	0.610	0.460	0.707	0.405	0.394	0.230	0.507	0.230	0.005	0.076	2.926	0.015	1.661	0.019	0.129
CD	0.836	1.319	2.029	1.161	1.131	0.659	1.453	0.659	0.015	0.218	8.395	0.043	4.765	0.055	0.370

P = Polyhouse, O= Open field.

T_1= 100% RDF+B @ 0.2%+Ca @ 0.2%, T_2= 100% RDF+Ca @ 0.2%, T_3= 100% RDF+B @ 0.2%, T_4= 75% RDF+B @ 0.2%+Ca @ 0.2%, T_5= 75% RDF+Ca @ 0.2%, T_6= 75% RDF+B, @ 0.2% T_7= 50% RDF+B @ 0.2%+Ca @ 0.2%, T_8= 50% RDF+Ca, @ 0.2% T_9= 50% RDF+B @ 0.2%, T_{10}= Control.

Table 2: Effects of the interaction of environment and micronutrients application efficiency on various yield parameters of chilli under polyhouse (P) and openfield (O) condition.

Interaction A × B	50% flowering (Days)	First fruit set (Days)	First fruit harvest (Days)	Last fruit set (Days)	No of fruit per plant	Fruit length (cm)	Av. fruit weight (g)	Fruit diameter (cm)	Yield/ plant (kg)	Pericarp thickness (mm)	Number of seed/ fruit	Dry weight of 100 seeds (g)	Plant height (cm)	Ascorbic acid content (mg/100 g)	Number of locules/ fruit
PT_1	42.66	48.00	76.00	149.00	20.00	8.66	140.00	6.33	2.80	3.74	190.00	0.4	125.00	0.53	3.00
PT_2	47.00	49.33	75.33	149.33	18.66	8.00	130.16	5.34	2.43	4.16	190.33	0.4	130.66	0.39	3.33
PT_3	46.00	49.33	76.00	150.33	18.66	8.00	133.66	5.33	2.49	4.33	186.66	0.5	124.63	0.19	3.00
PT_4	47.00	49.83	76.66	149.67	18.00	8.33	126.66	5.35	2.28	4.50	188.00	0.3	127.33	1.33	3.33
PT_5	41.33	46.16	72.66	152.00	20.36	10.33	145.33	9.00	3.05	5.43	187.33	0.5	140.26	0.55	4.00
PT_6	45.66	51.00	76.33	154.33	18.33	7.66	113.33	5.67	2.08	5.10	187.33	0.4	120.46	0.43	3.00
PT_7	40.66	46.00	69.66	156.00	21.00	10.33	152.35	9.00	3.35	6.10	180.66	0.5	155.43	1.62	4.66
PT_8	45.33	49.66	75.33	155.00	19.33	8.00	106.66	6.00	2.06	4.66	216.66	0.5	105.36	1.37	3.00
PT_9	46.33	51.00	78.00	150.66	18.67	7.66	104.00	5.34	1.94	4.66	191.66	0.4	113.16	0.48	3.00
PT_{10}	39.00	52.26	80.00	148.00	18.00	7.33	100.33	7.00	1.81	5.60	255.33	0.5	110.00	0.61	4.00
OT_1	45.00	52.66	73.33	148.00	18.33	7.33	86.55	6.00	1.96	3.26	190.33	0.45	106.66	0.28	3.22
OT_2	45.00	51.33	76.66	148.33	17.33	7.00	87.66	5.33	1.87	3.46	190.33	0.4	104.16	0.22	3.00
OT_3	48.67	54.67	84.66	148.33	13.66	8.00	84.03	5.00	1.69	3.70	186.66	0.4	102.00	0.56	3.00
OT_4	47.00	53.66	98.34	148.66	17.33	7.33	80.77	5.34	1.91	4.13	185.66	0.5	101.00	0.46	3.00
OT_5	42.66	49.33	71.01	150.00	18.66	8.00	95.33	7.33	2.15	4.56	188.00	0.4	120.00	0.45	3.44
OT_6	47.00	53.33	90.00	150.00	16.66	7.33	85.00	5.66	1.75	5.43	187.33	0.5	100.43	0.56	3.00
OT_7	43.33	48.66	71.33	149.67	18.66	9.00	96.32	7.00	2.35	4.50	180.66	0.5	130.36	0.67	3.22
OT_8	45.66	55.33	80.66	151.33	17.00	7.33	84.66	5.66	1.64	4.56	216.66	0.5	103.63	0.76	3.00
OT_9	47.00	54.67	83.00	149.33	15.66	7.00	79.55	5.33	1.56	4.26	191.66	0.5	100.46	0.85	3.00
OT_{10}	42.33	56.00	85.00	147.00	15.66	7.00	85.11	5.33	1.49	5.10	255.00	0.5	99.16	0.75	3.00
GM	44.73	51.11	78.49	150.24	18.08	7.981	114.96	6.11	2.07	4.56	197.31	0.45	130.36	0.653	3.24
SE(m)	0.863	0.206	1.000	0.573	0.558	0.325	0.716	0.103	0.007	0.034	1.309	0.007	0.743	0.086	0.05
CD	1.220	0.920	2.869	1.600	1.600	0.459	2.055	0.932	0.021	0.308	4.139	0.061	6.739	0.173	0.524

P= Polyhouse, O= Open field.

T_1= 100% RDF+B @ 0.2%+Ca @ 0.2%, T_2= 100% RDF+Ca @ 0.2%, T_3= 100% RDF+B @ 0.2%, T_4= 75% RDF+B @ 0.2%+Ca @ 0.2%, T_5= 75% RDF+Ca @ 0.2%, T_6= 75% RDF+B, @ 0.2% T_7= 50% RDF+B @ 0.2%+Ca @ 0.2%, T_8= 50% RDF+Ca, @ 0.2% T_9= 50% RDF+B @ 0.2%, T_{10}= Control.

a similar pattern was observed as T_7 again exhibited earliness, achieving first harvest in 71.33 days, followed by T_5 (71.01 days). It is happened as the microclimate of polyhouse is controlled and more stable than in the open field. This reduces plant stress and allow better uptake and utilization of nutrients applied as fertigation or soil amendments. Similar result of interaction were also observed by Timilsina and Khanal (2024). The control (T_{10}) showed the late maturity at 85.00 days, reinforcing the trend of delayed fruiting in the absence of micronutrient supplementation whereas polyhouse showed better result than open field. The superiority of treatment T_7 can be attributed to the synergistic action of boron and calcium.

The parameter days to last fruit harvest reflects the overall fruiting span and harvest duration of a crop. In polyhouse conditions, the number of days for harvesting was recorded in treatment T_7 (156.00 days) followed by T_5 at 152.00 days (Table 1). The least harvesting days (148.00) were noted in the control treatment (T_{10}). Interestingly, although T_7 showed a short duration numerically, its delayed start and irregular fruiting pattern likely reduced its agronomic efficiency whereas, as comparing with open field conditions, T_7 again recorded the longest fruiting duration (149.67 days) followed by T_6 (150.00 days) and T_5 at 150.00 days. The control (T_{10}) showed the shortest duration at 147.00 days. Moreover in terms of interaction openfield (148.00 days) condition having shortest harvests days then polyhouse (156 days), which implies that nutrient-deficient treatments might result in not only delayed fruit initiation but also a shortened harvest window.

In (Fig 2) under polyhouse conditions, the maximum number of fruits per plant was recorded in T_7 with 22.00 fruits (Table 1). These treatments were notably superior in comparison to control (T_{10}). Similar findings were reported by Hossain *et al*. (2025). In contrast, under open-field conditions, the highest fruit count was again observed in T_7 and T_5, each producing 18.66 fruits, which was significantly better than the control (T_{10}, with 15.66 fruits per plant). The results are accordance with findings of Dhaliwal *et al.* (2017). This indicates that even under field conditions, where environmental fluctuations can affect nutrient uptake and reproductive efficiency, the combination of B and Ca still positively influenced fruiting behaviour but, in terms of interaction open-field has lesser number of fruits then polyhouse as capsicum gained appropriate temperature in polyhouse.

Fruit length and fruit diameter are a vital quality attribute in capsicum, directly influencing consumer preference, market value and yield potential. Under polyhouse conditions, the maximum fruit length was observed in T_5 and T_7, both recording a mean fruit length of 10.33 cm. Similar results are observed by Khan *et al.* (2023). In contrast, the T_{10} exhibited the shortest fruit length (7.33 cm) whereas, open field conditions, again, T_7 produced the longest fruits (9.00 cm). The control (T_{10}) in comparison remained the lowest with (7.00 cm). According to the interaction the highest length (10.33) noted in T_7 in polyhouse whereas, in open field reached only a length of 9.00 cm in T_7.

The average fruit weight is a major yield-contributing factor and directly reflects the impact of nutrient management practices on the physiological development of capsicum fruits. Table 1, revealed that under the polyhouse, the highest fruit weight was recorded in T_7 with 152.35 g, followed by T_5 at 145.33 g). T_{10} produced fruits with significantly lower weight (100.33 g), indicating the advantage of nutrient-enriched treatments. In the open field, T_7 again exhibited superior performance with 96.32g, whereas the control T_{10} remained lowest at 85.11 g. In terms of interaction treatment (Table 2) T_7 gained the highest fruit weight in polyhouse while T_7 in open field reached only 96.32 g. The results are in close association with Balai *et al.* (2017) and Rawat *et al.* (2024). Due to various environmental factors the fruit weight in open field is affected.

The highest fruit diameter was recorded in T_5 and T_7 under polyhouse, both registering 9.00 cm, considerably higher than the control (T_{10}). The addition of calcium and boron promotes better fruit enlargement. In the open field, the trend remained similar, with T_5 showing the maximum diameter (7.33 cm), followed by T_7 (7.00 cm). In contrast, the control treatment recorded a fruit diameter of only 5.00 cm, indicating inferior fruit development. This highlights the positive role of calcium and its synergistic effect with boron, in enhancing fruit morphology under both controlled and open environments. In terms of interaction largest diameter attain by T_5 and T_7 (9.00 cm) and openfield attain diameter upto (7.33 cm) in T_7. The interaction analysis revealed that T_7 had the most favorable impact on fruit diameter. Similar positive effects of micronutrients on various fruit parameters were also notice by Hossain *et al*. (2025).

The substantial variation in yield per plant was observed, under the polyhouse, the highest yield per plant was recorded in T_7 (50% RDF + B + Ca) with 3.35 kg, (Table 1). Similar results were cited by Devi *et al.* (2022) but T_{10} showed a lower yield of 1.81 kg, demonstrating the benefit of integrated nutrient applications. In the open field, T_7 again produced the highest yield per plant (2.35 kg), while the control (T_{10}) yielded only 1.49 kg. The superior performance of T_7 across both environments can be attributed to the synergistic effect of boron and calcium, which are known to enhance flowering, fruit set and nutrient translocation. In terms of interaction highest yield in polyhouse in treatment T_7 with 3.35 kg while in open-field condition showed lowest T_7 (2.35 kg). Calcium and boron play complementary roles in cell wall formation, membrane stability and overall plant productivity (Nayana *et al*., 2026). Polyhouse shown better performance in terms of yield as capsicum growing in a suitable environment whereas in open-field various environmental stresses affect the plant which affect the yield. These results are similar to the findings of Azad *et al.* (2021). Pericarp thickness play a vital role in the quality attribute, firmness, shelf life, transportability and consumer preference. The thickest pericarp was recorded high in T_7 (6.10 mm) and low in T_{10} (5.60 mm) in the polyhouse (Table 1). Under open field conditions, T_5 and T_4 exhibited the thickest pericarp with 4.56 mm and 4.13 mm, respectively, whereas T_{10} (control) recorded 5.10 mm, slightly higher than many treatments but still lower in overall performance compared to T_7 under the polyhouse. In terms of interaction polyhouse shown highest pericarp thickness in T_7 (6.10 mm) and open field shown less pericarp thickness 4.56 in T_5 and T_4. Due to fluctuating environmental stresses pericarp thickness affected.

The maximum number of seeds per fruit was recorded in T8 under both the condition. Heavier seeds typically indicate better nutrient accumulation, which contributes to higher germination rates and stronger seedlings. The maximum dry weight was observed in T_4, followed by T_3 and T_5 with 0.5 g each under polyhouse conditions (Table 1). The control treatment (T_{10}) also recorded a comparable seed weight of 0.5 g, indicating adequate seed development in untreated plants, though not significantly superior to treated ones. In the open field, several treatments including T_4, T_7, T_8, T_9 and T_{10} maintained a consistent dry seed weight of 0.5 g, whereas other treatments showed slightly lower values ranging from 0.4 g to 0.45 g. In terms of interaction the polyhouse and open field both have equal dry weight of seeds. Notably under T_7, the polyhouse condition consistently recorded higher seed weight as compared to the open field.

Plant height varied across different nutrient treatments under both the conditions, reflecting the differential effect of nutrient combinations on vegetative growth. T_7 showed the maximum plant height as compare to T_{10} under both the conditions. In terms of interaction longest height is observed in treatment T_7 (155.43 cm) while in open field the T_7 only reached a height of 130.36 cm. The similar trend of results was also reported by Tahir *et al*. (2013) and Rawat *et al.* (2024).

The considerable variations for ascorbic acid were found across the treatments in both the conditions. Under polyhouse conditions, the highest ascorbic acid content was observed in T_7 (1.62 mg/ml). These treatments, especially T_7, outperformed the T_1 (0.61 mg/ml). In open field conditions (Fig 3), although overall ascorbic acid levels were lower than in polyhouse, T_9 and T_8 still showed relatively higher values at 0.85 mg/ml and 0.76 mg/ml, respectively, compared to the control's 0.75 mg/ml. In terms of interaction higher vitamin C concentration was found in polyhouse-grown capsicum 1.62 mg/ml whereas in openfield 0.85 mg/ml. Studies have showed that the interaction of nutrient management and polyhouse conditions significantly enhances capsicum growth, yield and quality, owing to improved nutrient use efficiency and controlled environmental conditions (Jat *et al*., 2022). The similar results was also reported by Ramachandrappa *et al*. (2010) in chilli.

The treatment T_5, T_7 and T_{10} contain 4 locules in both the conditions that denoted as good as more the number of locules, the fruit is directly healthy and acquire good fruit weight. Adequate calcium contributes to better cell division and stronger ovary development, ensuring successful fruit formation post-pollination (Mishra *et al.,* 2019). Canopy structure influences light interception, which directly affects photosynthetic efficiency and productivity in vegetable crop (Zhang *et al*., 2023).

CONCLUSION

The study revealed significant individual and interaction effects of environment, fertilizer method and micronutrient levels on all measured growth, yield and quality parameters. The polyhouse condition and combined application method of 50% RDF + B @ 0.2%+ Ca @ 0.2% gives high yield per plant (3.35 kg), followed by T_5 (75% RDF + Ca @ 0.2%). The highest ascorbic acid content (1.62 mg/ml) was observed with the application of 50% RDF + B @ 0.2%+ Ca), followed by T_8 (50% RDF + Ca@ 0.2%) with 1.37 mg/ml, under polyhouse conditions. It is concluded that the integration of boron and calcium with recommended doses of NPK significantly improves capsicum growth, yield and quality. Among the treatments, T_7 consistently stood out as the best performer, making it the most efficient and cost-effective option for sustainable capsicum cultivation.

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Disclaimers

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Conflict of interest

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